Final Technical Report
Refining estimates of lithosphere rheology and earthquake parameters along the San Andreas fault system through Bayesian inversion of multiple data sets

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Technical Abstract

It is well known that slip rate estimates from geodetic data are non unique because they depend on model assumptions and parameters which are often not known *a priori*. Estimates of fault slip rate on the Mojave segment of the San Andreas Fault system derived from elastic block models and GPS data are significantly lower than estimates from geologic data. To determine the extent to which the slip rate discrepancy might be due to the oversimplified models of the rheology of the lithosphere, we have developed 2D and 3D earthquake cycle models to simultaneously estimate fault slip rates and lithosphere viscosity structure in southern California. The models consist of episodic earthquakes in an elastic crust overlying a viscoelastic asthenosphere that is has either a uniform or layered viscosity structure. We use GPS measurements of postseismic relaxation following the 1992 Landers earthquake, triangulation measurements spanning 1932-1977, GPS measurements of the contemporary velocity field, and paleoseismic data along the San Andreas fault.

With 2D models we infer lower crustal (15-30 km depth) viscosity of $\sim 10^{19} - 10^{20}$ Pa s, uppermost mantle (30-60 km) viscosity of $\sim 10^{20-22}$ Pa s, and underlying upper mantle viscosity of $\sim 10^{18} - 10^{19}$ Pa s, consistent with inferences from laboratory experiments of relatively high viscosity lithospheric mantle and lower viscosity lower crust and underlying asthenospheric mantle. We infer a 20-30 mm/yr slip rate on the San Andreas fault, in agreement with the lower end of geologic estimates.

The results from 3D models are still preliminary, but at this point confirm the results from 2D models. In particular, 3D earthquake cycle models with uniform viscoscity asthenosphere predict 15 mm/yr of slip on the Mojave segment of the San Andreas fault, consistent with elastic block models, and inconsistent with geologic estimates.

Background and approach

Geologic and paleoseismic studies indicate that the San Andreas fault slips 25-35 mm/yr along the Mojave segment (e.g., [*Sieh and Jahns*(1984)], [*Weldon* et al.(2004)]). The remaining 15-25 mm/yr needed to keep up with the 50 mm/yr of total shift across the plate boundary is presumed to occur on neighboring faults, mostly within the Eastern California Shear Zone (e.g., [*Meade and Hager*(2005)]). Estimates of slip rate on the Mojave segment of the San Andreas Fault system inferred from elastic dislocation models and GPS data are inconsistent with estimates using geologic data. Elastic block models predict lower slip rates of about 15 mm/yr ([*Becker* et al.(2004)], [*Meade and Hager*(2005)]). Elastic block models incorporate steady, long-term rigid block motion and interseismic elastic strain accumulation due to locking of faults in the upper seismogenic crust modeled with dislocations in an elastic half-space (e.g., [*Savage and Burford*(1973)], [*McCaffrey*(2002)]). It is well known that slip rate estimates from geodetic data depend strongly on model assumptions about rheology of the crust and mantle, and therefore any discrepancies between estimates using geologic and geodetic data might be attributed to model assumptions.

2D models

In an attempt to resolve these discrepancies, we develop a model that enables us to integrate various data sources covering a broad range of time periods into a joint estimate of fault slip and viscosity structure. The Mojave region is ideal for this study because of the abundance of geodetic and paleoseismic data. We have GPS time-series data of postseismic relaxation following the 1992 Landers earthquake in the Mojave desert (http://quake.usgs.gov/research/deformation/gps/auto/LandersPro/), triangulation data spanning 1932-1977 ([*NGS*(2004)]), and GPS measurements of the contemporary velocity field (http://epicenter.usc.edu/cmm3/; Figure 1). In addition, a detailed history of past earthquakes is beginning to emerge with continued analysis of paleoseismic excavations along the San Andreas fault ([*Weldon* et al.(2004)], [*Hilley and Young*(2006)]).

Our 2D earthquake cycle model consists of an infinitely long strike-slip fault in an elastic crust overlying two Maxwell viscoelastic layers and a Maxwell viscoelastic half-space (Figure 2). The viscoelastic regions represent the lower crust, uppermost mantle, and upper mantle. We consider a distinct uppermost-mantle layer to approximate a possible relatively viscous lithospheric mantle lid separating a weaker lower crust and asthenospheric upper mantle. The one-dimensional analog of a Maxwell viscoelastic solid is a spring connected to a dashpot, which is a plunger in a cylinder filled with a Newtonian viscous fluid.

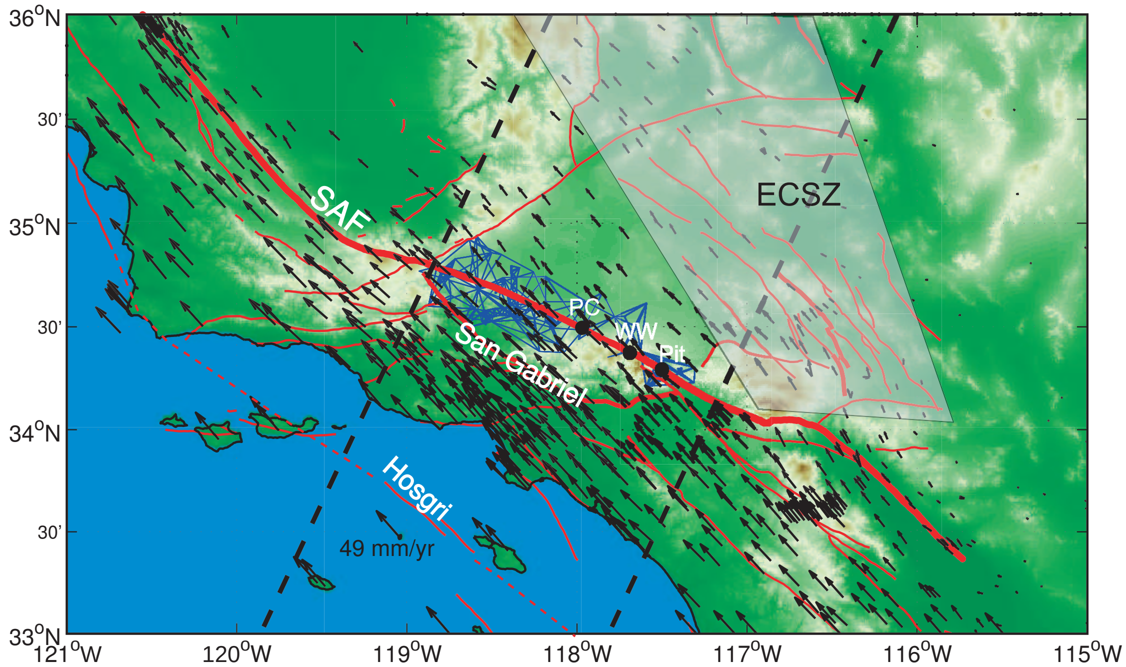

Figure 1: Location map of study area showing distribution of geodetic data and locations of paleoseismic excavation sites along the San Andreas fault. GPS velocities relative to North America. Blue mesh shows triangulation network within 10 km of the San Andreas fault. GPS data within dashed lines are used in this study. The Eastern California Shear Zone (ECSZ) is outlined with the gray box. Paleoseismic sites: PC - Pallett Creek, WW - Wrightwood, PT - Pitman Canyon.

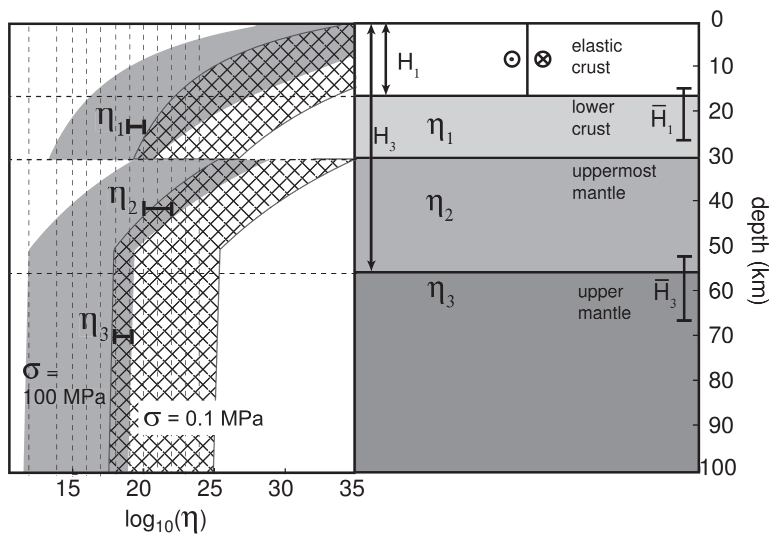

Figure 2: Theoretical viscosity distribution and geometry of multilayer viscoelastic earthquake cycle model. Rheological parameters to be solved for are viscosities of lower crust, η_1, uppermost mantle, η_2, and upper mantle, η_3, as well as depth to bottom of elastic crust, H_1, and depth to top of mantle, H_3. $\overline{H}_1$ and $\overline{H}_3$ denote approximate 2σ uncertainty ranges from inversion. Theoretical viscosity profile is constructed from laboratory derived creep laws using a range of experimental values for crustal and mantle materials at two different stress levels (0.1 and 100 MPa).

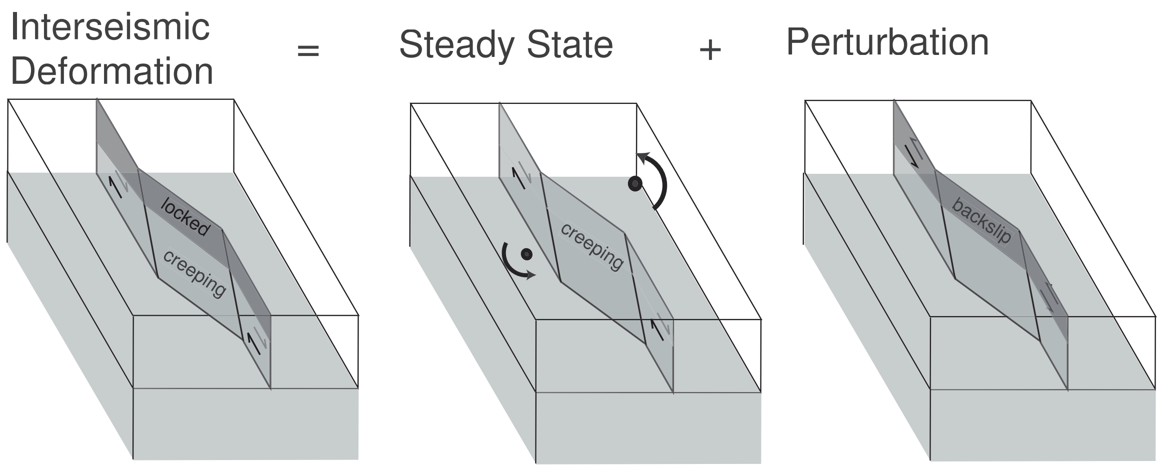

Figure 3: Illustration of the back slip model concept as a sum of a long-term, steady-state velocity field and a perturbation to the velocity field due to locking of faults during the interseismic period.

3D models

A description of the 3D model used in this work is in a paper in preparation. We refer to the model as a plate-block model because we assume the lithosphere is divided into blocks bounded by faults in an elastic plate (lithosphere) overlying a viscoelastic substrate (asthenosphere). The model construction is based on the backslip concept first devised by [*Savage and Burford*(1973)], [*Savage and Prescott*(1978)], and [*Savage*(1983)] in which a steady-state (long-term) velocity field is perturbed by locking of faults between earthquakes modeled as dislocations in an elastic plate or elastic half-space (Figure 3). In the plate-block model the long-term motions of blocks and the slip rates on bounding faults are prescribed, similar to the elastic half-space block models of [*McCaffrey*(2002)] and [*Meade and Hager*(2005)]. However our model for long-term deformation is different from [*McCaffrey*(2002)] and [*Meade and Hager*(2005)] in that we incorporate vertical displacements associated with dip-slip on non-vertical faults and we do not allow fault-normal velocity discontinuities (tensile slip). These conditions necessitate long-term distortion of the fault-bounded blocks. We model interseismic deformation by imposing backslip and periodic earthquakes on portions of faults that are locked between earthquakes. Because the asthenosphere is modeled as viscoelastic, the periodic earthquake sequences produce time-variable surface velocities due to viscous flow. The construction of the earthquake cycle is identical to the 2D formulation of [*Savage and Prescott*(1978)].

Results

2D models

The inferred long-term slip rate on the San Andreas fault is 20-28 mm/yr, at the lower end of the 25-35 mm/yr estimate from geologic data. Figure 4 shows the fit to the data.

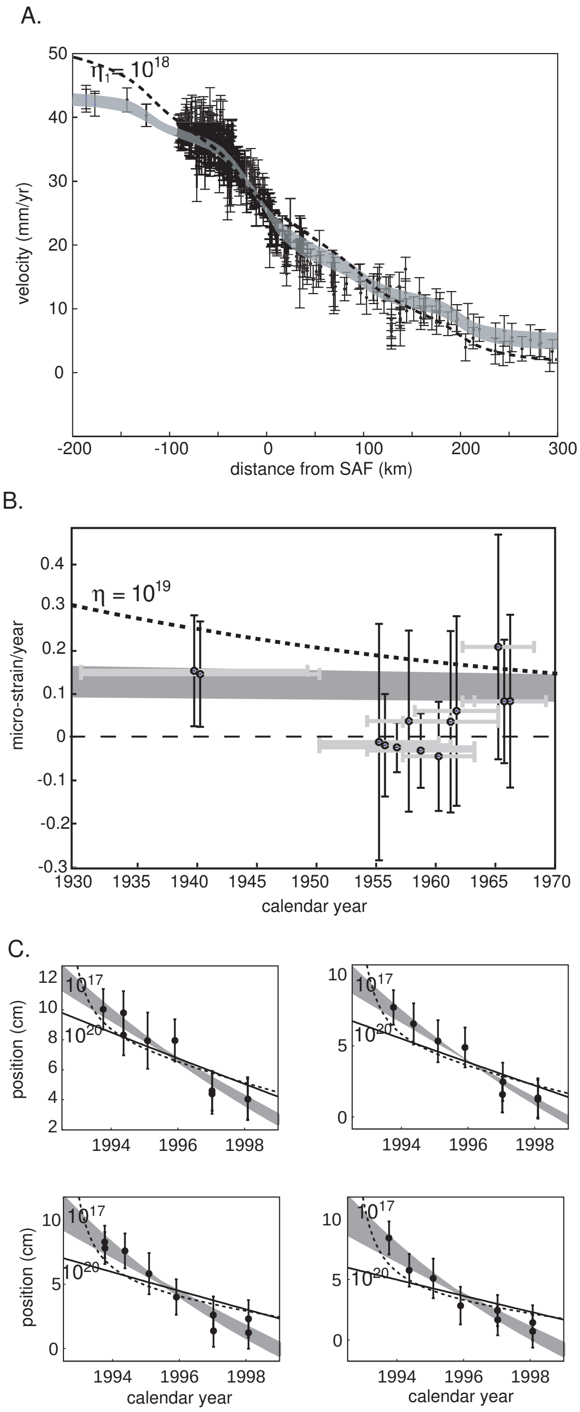

Figure 4: Fit to the data. Gray shading shows 95% confidence bounds on model predictions. A. Fit to contemporary GPS velocities. Dashed curve show best fit for viscous channel model with lower crustal viscosity fixed at 10^{18} Pa s. B. Fit to strain rate estimates from triangulation data. Vertical error bars are 2σ errors. Horizontal bars denote time period over which strain rate is averaged. Dashed curve shows best fit assuming uniform lower crust and mantle viscosity of 10^{19} Pa s. C. Fit to four post-Landers GPS time-series. Dashed and solid curves show results with upper mantle viscosity fixed to 10^{17} Pa s and 10^{20} Pa s.

The 95% confidence intervals on lithosphere layer thicknesses and viscosities are plotted in Figure 2. It is quite remarkable, given that there were no prior constraints on viscosity, that the viscosities are resolved to within 1-2 orders of magnitude in each layer. It is also quite interesting that the viscosity distribution with depth follows the general pattern expected from laboratory measurements; the average mantle viscosity is lower than the average upper mantle and lower crustal viscosities and the lower crustal viscosity is lower than the uppermost mantle viscosity. Also, values of 52-66 kn for H_3, the depth to the top of the low-viscosity upper mantle asthenosphere, are consistent with independent evidence for the lack of a thick lithospheric mantle lid in the western US ([*Goes and van der Lee*(2002)], [*Freed and Bürgmann*(2004)]).

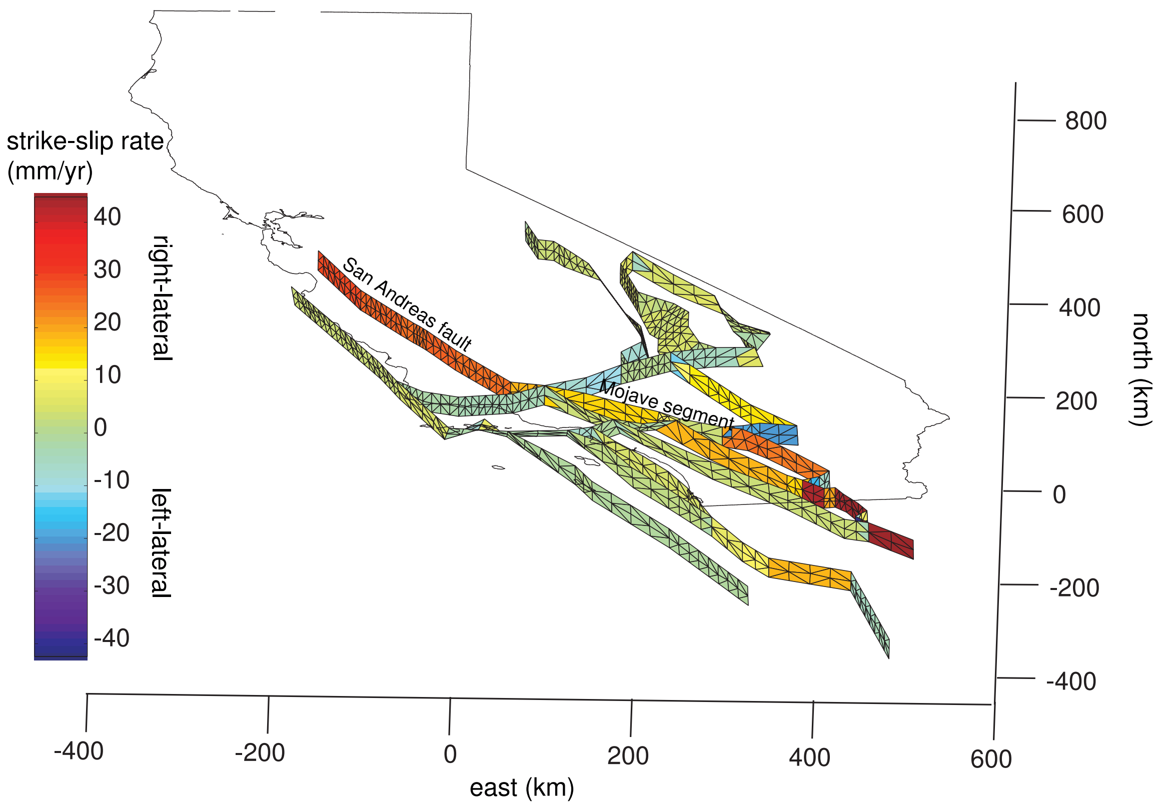

Figure 5: 3D model inversion results for strike-slip rates.

3D models

We generated a block model using fault geometry adopted form the SCEC Community Fault model data base (http://structure.harvard.edu/cfm-r_project/cfmr.html) as shown in Figure 5. We assumed an elastic thickness of 30 km and we assumed faults are locked interseismically down to 15 km depth. We assumed an asthenosphere viscosity of 10^{19} Pa s and assumed timing of past earthquakes using the data base of WGCEP 2007 (http://www.wgcep.org/).

The estimated strike-slip component of fault slip rate is shown in Figure 5. Consistent with the elastic block models, we obtain a slip rate of about 15 mm/yr for the Mojave segment of the San Andreas fault, about 10 mm/yr slower than the geologic estimates.

Considering the 2D and 3D model inversion results, the tentative conclusion at this point is that the only way to produce model slip rates similar to geologic estimates of 25-35 mm/yr on the Mojave segment is to model the asthenosphere with multiple viscoelastic layers with different viscosities.

This work shows that slip rate estimates using geologic data can be strongly sensitive to the chosen earth model.

Reports Published

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